

## REVIEW ARTICLE

## Cyclic nucleotide phosphodiesterases as targets for treatment of haematological malignancies

Adam LERNER\*† and Paul M. EPSTEIN‡<sup>1</sup>

\*Evans Department of Medicine, Section of Hematology and Oncology, Boston Medical Center, Boston, MA 02118, U.S.A., †Department of Pathology, Boston University School of Medicine, Boston, MA 02118, U.S.A., and ‡Department of Pharmacology, University of Connecticut Health Center, Farmington, CT 06030, U.S.A.

The cAMP signalling pathway has emerged as a key regulator of haematopoietic cell proliferation, differentiation and apoptosis. In parallel, general understanding of the biology of cyclic nucleotide PDEs (phosphodiesterases) has advanced considerably, revealing the remarkable complexity of this enzyme system that regulates the amplitude, kinetics and location of intracellular cAMP-mediated signalling. The development of therapeutic inhibitors of specific PDE gene families has resulted in a growing appreciation of the potential therapeutic application of PDE inhibitors to

the treatment of immune-mediated illnesses and haematopoietic malignancies. This review summarizes the expression and function of PDEs in normal haematopoietic cells and the evidence that family-specific inhibitors will be therapeutically useful in myeloid and lymphoid malignancies.

**Key words:** cAMP, cancer therapy, glucocorticoid, leukaemia, methylxanthine, phosphodiesterase.

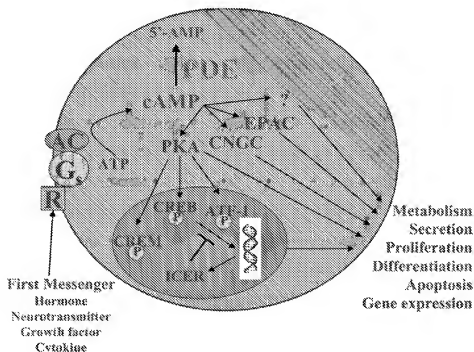
## INTRODUCTION

Following the identification of cAMP in 1958 by Rall and Sutherland [1], research focused for more than a decade on elucidating the role that this 'second messenger' played in regulating metabolic pathways, as well as identifying the enzymes responsible for cAMP synthesis and catabolism [1–3]. By the 1970s, however, cAMP was implicated as a regulator of cell growth (reviewed in [4–6]), and several investigators reported that elevation of cAMP levels induced arrest of proliferation or cell death in susceptible normal or malignant lymphoid populations [7–10]. Upon identifying cAMP as a second messenger, Rall and Sutherland [1] also reported the presence in tissue extracts of a caffeine (1,3,7-trimethylxanthine)-sensitive enzymatic activity, cyclic nucleotide PDE (phosphodiesterase), capable of hydrolysing cAMP. It became apparent in the 1970s that multiple forms of PDE existed [11,12] and that different forms could be inhibited differentially by pharmacological agents [12–15]. Reports in the 1970s also demonstrated that methylxanthines suppressed lymphocyte activation and proliferation [16–18] and that PDE activity in leukaemic cells was as much as 10–20-fold higher than that in normal quiescent lymphocytes [19,20]. From these observations, it was proposed, 25–30 years ago, that PDEs may be potential therapeutic targets in the treatment of haematological malignancies [12,19–21].

It is now well accepted that PDEs control a myriad of cellular processes through their ability to hydrolyse and thus control the levels of the second messenger signalling molecules, cAMP and cGMP [22,23] (Figure 1). In addition to controlling the steady-state levels of cyclic nucleotides, it has become clear that PDEs also control the spatial and temporal components of cAMP and cGMP signalling [24–26]. PDEs are encoded by at least 21 different genes, grouped into 11 different gene families, based on sequence similarity, mode of regulation and preference for cAMP or cGMP as substrate [27,28]. These 11 PDE gene families and some of their properties are presented in Table 1. With the existence of multiple transcription-initiation sites, as well as alternatively spliced forms of many of these genes, more than 50 different forms of PDE have been identified and cloned to date, many of which vary with respect to tissue distribution and the intracellular signalling pathways with which they interact. A considerable number of reviews both on PDEs in general, as well as on roles for PDEs in controlling specific cellular functions, have been written in recent years, including potential roles for PDEs as targets for treating inflammatory diseases [29–32] and cancer [21,33–35]. The present review will examine the current evidence that cyclic nucleotide PDE inhibitors will prove to be beneficial as therapeutic agents in the treatment of lymphoid and myeloid malignancies.

Abbreviations used: AKAP, A-kinase anchoring protein; ALL, acute lymphoblastic leukaemia; AML, acute myeloid leukaemia; APL, acute promyelocytic leukaemia; ATRA, all-trans-retinoic acid; BAD, Bcl-2/Bcl-X<sub>L</sub> antagonist, causing cell death; Bcl-2, B-cell lymphoma 2 anti-apoptotic protein; CLL, chronic lymphocytic leukaemia; COPD, chronic obstructive pulmonary disease; 8-CPT-2Me-cAMP, 8-(4-chlorophenylthio)-2'-O-methyladenosine-3',5'-cyclic monophosphate; CRE, cAMP-response element; CREB, CRE-binding protein; DLBCL, diffuse large B-cell lymphoma; EAE, experimental autoimmune encephalomyelitis; EHNA, erythro-9-(2-hydroxy-3-nonyl)adenine; EPAC, exchange protein activated by cAMP; ERK, extracellular-signal-regulated protein kinase; GAF, a conserved domain found in mammalian cGMP-binding PDEs; Anabena adenylate cyclases and *Escherichia coli* FhlA; GR, glucocorticoid receptor; GRE, glucocorticoid-responsive element; HPBL, human peripheral blood lymphocyte; IBMX, 3-isobutyl-1-methylxanthine; IκB, inhibitor of nuclear factor-κB; IL, interleukin; LPS, lipopolysaccharide; 8-MM-IBMX, 8-methoxymethyl-isobutylmethylxanthine; NFAT, nuclear factor of activated T-cells; NF-κB, nuclear factor-κB; PAS, Per-Arm-Sim domain; PDE, cyclic nucleotide phosphodiesterase; PHA, phytohaemagglutinin; PI3K, phosphoinositide 3-kinase; PKA, cAMP-dependent protein kinase; PKB, protein kinase B; PML, promyelocytic leukaemia; PP2A, protein phosphatase 2A; RAR, retinoic acid receptor; RNAi, RNA interference; Rp-8-BrcAMPs, 8-bromoadenosine-3',5'-cyclic monophosphothioate, Rp-isomer; SCID, severe combined immunodeficient; TCR, T-cell receptor; TNF, tumour necrosis factor; UCR, upstream conserved region.

<sup>1</sup> To whom correspondence should be addressed (email epstein@ns1.uchc.edu).



**Figure 1** Role of PDEs in regulation of signal transduction

In the model of the second-messenger concept originally put forth by Sutherland and colleagues [286], first messengers, such as hormones, neurotransmitters, cytokines and growth factors, upon interacting with receptors on the cell surface, generate the production of a 'second messenger' such as cAMP, which then redirects the machinery of the cell, affecting many physiological processes. Currently, three different types of effector proteins to which cAMP can bind and carry out its actions are known: PKA [296], EPAC [251,252] and CNGCs (cyclic nucleotide-gated channels) [297]. In addition to these three known effector pathways for cAMP action, it remains possible that other currently undescribed cAMP effectors exist as well. Investigators examining cAMP inhibition of IL-5 production by T-cells, suppression of neutrophil apoptosis and inhibition of PKB/Akt leading to apoptosis in DLBCL cell lines have reported that these cAMP-mediated phenomena occur independently of currently described cAMP effector proteins [125,213,298]. cAMP effector molecules can also affect cellular processes directly through tethering mechanisms, as has been shown for the PKA catalytic subunit, which forms complexes with the GR,  $\text{I}\kappa\text{B}$  and NF- $\kappa\text{B}$  [258,299]. Tethering of the PKA catalytic subunit in a complex with  $\text{I}\kappa\text{B}$  and NF- $\kappa\text{B}$  provides a novel cAMP-independent means of regulating PKA, whereby degradation of  $\text{I}\kappa\text{B}$  disinhibits PKA, allowing it to phosphorylate and activate NF- $\kappa\text{B}$  [299]. PKA is uniformly expressed and EPAC is expressed in specific subsets of haematopoietic cells, and these two effectors are probably responsible for mediating almost all of the known cAMP signalling events in these cells. Although CNGCs have not been explored in haematopoietic cells, they are expressed in spleen and thymus [300], and future investigations may uncover a role(s) for these effectors in these cells as well. Activation of PKA by cAMP leads to changes both in cytosolic proteins and in gene transcription through phosphorylation of cAMP-responsive nuclear factors such as CREB, CREM (CRE modulator) and ATF-1 (activating transcription factor 1) [301]. Additionally, a powerful repressor, ICER (inducible cAMP early repressor), can be formed from the CREM gene, following stimulation of cAMP signalling, probably as a feedback mechanism to terminate cAMP-induced gene expression [301]. ICER has been shown to function in T-cells as a transcriptional repressor and to be induced by the PDE4 inhibitor, rolipram, in osteoblasts [302,303]. PDEs, by regulating cAMP levels, play a central role in modulating all of these cAMP signalling pathways and consequent physiological responses. AC, adenylate cyclase; R, receptor (seven-membrane-spanning G-protein-coupled metabotropic receptor).

## PDE FAMILY FUNCTION AND EXPRESSION IN NORMAL HAEMATOPOIETIC CELLS

In this section, we will review the expression patterns of PDE families within the haematopoietic system, the signalling pathways known to be regulated by these enzymes within haematopoietic cells and the availability of specific inhibitors either experimentally or clinically. Although characterization of the PDEs within normal haematopoietic cells may be at least partially predictive of their expression within corresponding haematological malignancies, an equally important aspect of this literature is that it may allow us to predict the likely haematological toxicity of PDE inhibitor therapy.

### PDE1

PDE1 enzymes are widely expressed calcium- and calmodulin-dependent PDEs that catabolize both cAMP and cGMP [36–38]. The PDE1 gene family consists of three genes: PDE1A, PDE1B and PDE1C. All three of these PDE1 gene products exhibit a relatively high affinity for cGMP ( $K_m \approx 1\text{--}5\text{ }\mu\text{M}$ ), but differ in their affinities for cAMP, with PDE1C exhibiting the highest affinity ( $K_m \approx 1\text{ }\mu\text{M}$ ), PDE1B having an intermediate affinity

( $K_m \approx 7\text{--}24\text{ }\mu\text{M}$ ), and PDE1A showing the lowest affinity ( $K_m \approx 50\text{--}100\text{ }\mu\text{M}$ ). As a result of PDE1 calmodulin dependence, expression of this family of enzymes allows calcium signalling pathways to regulate cyclic nucleotide-dependent signalling. Although several inhibitors showing some selectivity for PDE1 have been available for a while, none are highly potent, nor truly selective for inhibition of PDE1. Vinpocetine [39] and 8-MM-IBMX (8-methoxymethyl-isobutylmethylxanthine) [40], the most commonly used PDE1 inhibitors, were originally reported to be selective for inhibition of PDE1, but subsequent studies showed 8-MM-IBMX to not be as selective as originally reported [41], and recent studies have shown that vinpocetine can inhibit other PDEs, particularly PDE4B, in the same concentration range ( $\text{IC}_{50} = 22\text{ }\mu\text{M}$ ) as that for the PDE1 enzymes ( $\text{IC}_{50} = 5\text{--}25\text{ }\mu\text{M}$ ) (Vince Florio, personal communication). Complicating further the use of vinpocetine for examination of cellular PDE1 effects were reports that PDE1C isolated from insulinoma cells is resistant to vinpocetine inhibition [42] and that sodium channel activation can be inhibited by vinpocetine independently of its effects on PDE [43]. The dual PDE1/PDE5 inhibitors, SCH51866 and zaprinast (M&B 22938) have sometimes been used to explore functions of PDE1, especially in tissues where PDE5

**Table 1** PDE gene families

The Table shows the eleven PDE gene families, the known genes within them, their affinity constants for cAMP and cGMP, and commonly used pharmacological inhibitors for each of the families. The substrate affinity constants listed are approximate, and, where given, ranges represent the different  $K_m$  values reported for these family members in the references cited.

Family	Type	Genes	$K_m$ cAMP ( $\mu$ M)	$K_m$ cGMP ( $\mu$ M)	Commonly used inhibitors*	References
PDE1	CaM-dependent	1A 1B 1C	50–100 7–24 1	5 3 1	Vinopetine (5–25) 8-MM-IBMX (4)	[35–38,272–276]
PDE2	cGMP-stimulated	2A	30	10	EHNA (1)	[59,68,69,277]
PDE3	cGMP-inhibited	3A/B	0.2–0.5	0.02–0.2	Cilostamide (0.005) Milirone (0.3)	[80,278,279]
PDE4	cAMP-specific	4A–D	1–4	–	Rolipram (1) RO 20-1724 (2) Piclamilast (0.001) Sildenafil (0.003) Zaprinast (0.3)	[130,280–283]
PDE5	cGMP-specific	5A	–	1–5	Dipyridamole (0.9) Zaprinast (0.15)	[240,241,284–287]
PDE6	Photoreceptor	6A–C	–	20	Dipyridamole (0.4)	[288,289]
PDE7	cAMP-specific	7A/B	0.03–0.2	–	Dipyridamole (42, 7A, 0.5–9, 7B)	[150–152,290–292]
PDE8	cAMP-specific	8A/B	0.04–0.15	–	Dipyridamole (4–8, 8A, 23–40, 8B)	[162–164,166]
PDE9	cGMP-specific	9A	–	0.07–0.39	Zaprinast (30) SCH 51866 (2)	[170,171,233]
PDE10	Dual substrate	10A	0.05–0.26	3–9	Papaverine (0.03)	[173,174,179,294]
PDE11	Dual substrate	11A	1–6	0.5–4	Tadalafil (0.07) Zaprinast (11–33) Dipyridamole (0.3–1.8)	[183–185,187,188]

\* The numbers in parentheses are the approximate reported  $K_i$  or  $IC_{50}$  values for inhibition of that PDE gene family, given in  $\mu$ M. Note: the non-specific methylxanthine inhibitor IBMX inhibits all of the PDE families with the notable exception of the PDE8 and PDE9 gene families, which appear to be resistant to IBMX inhibition.

is not expressed [44,45]. The discovery that phenothiazine antipsychotics [46], as well as several other classes of pharmacological agents [47], bind to calmodulin and antagonize its stimulation of PDE1, led to the wide use of these agents, especially trifluoperazine (e.g. [48]), to probe a PDE1-controlled function. However, given the wide range of cell functions that are controlled by calmodulin, it is difficult to conclude that a process inhibited by these agents is necessarily controlled by PDE1. Another approach that has been taken is a gene-regulation approach to selectively block PDE1 expression [49]. In general, where selective inhibitors of a given PDE form are not available to probe for a physiological function of that PDE, the approach of selectively inhibiting the expression of that PDE isoform by use of oligodeoxynucleotide antisense [50] or RNAi (RNA interference) [51] techniques should prove quite useful. Recently, for example, Lynch et al. [52] used RNAi techniques in HEK-293 (human embryonic kidney) cells to demonstrate that knockdown of PDE4D5, but not other expressed PDE4 isoforms, amplifies isoproterenol-stimulated phosphorylation of the  $\beta_2$ -adrenergic receptor by PKA (cAMP-dependent protein kinase) and  $G_i$ -mediated activation of ERK (extracellular-signal-regulated kinase). Clearly, though, there is still a need for better, more highly selective PDE1 inhibitors for exploration of the physiological functions of this family of enzymes.

Although the majority of studies on this family of enzymes focus on their role in the cardiovascular system and brain, Jiang et al. [49] detected PDE1B1 by RT (reverse transcriptase)-PCR in activated HPBLs (human peripheral blood lymphocytes). Both transcript and enzymatic activity are induced following stimulation of HPBLs or T-cells with the T-cell mitogen PHA (phytohaemagglutinin) or CD3/CD28 respectively [49,53]. Inhibition of PDE1 in CD3/CD28-stimulated T-cells with 8-MM-IBMX or vinopentine partially blocked IL (interleukin)-13 production [53]. PDE1 activity was not detected in resting human CD19<sup>+</sup>

peripheral blood B-cells [54], but was in B-lymphoblastoid cell lines [55]. PDE1 enzymatic activity is present at very low levels in human peripheral blood monocytes and increases markedly during differentiation of monocytes to dendritic cells [56]. The splice isoform PDE1B2 is selectively up-regulated following differentiation of monocytes to macrophages because of the use of a different promoter [57]. Of note, mice rendered deficient for PDE1B by homologous recombination have exaggerated locomotor activity, but no gross haematopoietic defects were reported [58].

## PDE2

PDE2 hydrolyses both cAMP and cGMP with non-linear kinetics displaying strong positive homotropic co-operativity. Half-maximal velocities for cAMP and cGMP hydrolysis are at approx. 30  $\mu$ M and 10  $\mu$ M respectively [59]. Additionally, PDE2 possesses two high-affinity non-catalytic cGMP-binding domains near its N-terminal end, termed GAF (a conserved domain found in mammalian cGMP-binding PDEs, *Anabaena* adenylate cyclases and *Escherichia coli* FhlA) domains, to which cGMP binds with a  $K_d$  of approx. 0.3  $\mu$ M and stimulates the enzymatic hydrolysis of PDE2 for cAMP [60–62]. The stimulation of PDE2 cAMP hydrolysis by cGMP is not a result of a change in  $V_{max}$ , rather, the binding of cGMP to one of the GAF domains allosterically alters PDE2 resulting in less co-operative behaviour, thus producing a lowering of the apparent  $K_m$  for cAMP. This reduction in co-operativity upon cGMP binding provides a means for small increases in cGMP to dramatically stimulate the hydrolysis of cAMP by PDE2. Indeed, as an example of this, it was demonstrated recently that ANP (atrial natriuretic peptide) stimulation of particulate guanylate cyclase in intact bovine zona glomerulosa cells led to the decrease of cellular cAMP from high micromolar levels to sub-micromolar levels in 15–20 s through cGMP

stimulation of cAMP hydrolysis by PDE2 [26]. GAF domains are also present in PDEs 5, 6, 10 and 11, although it has not been demonstrated that cGMP binding to these domains on PDEs other than PDE2 leads to activation of the catalytic activity, and the functional consequences of cGMP binding to these other PDE forms is still not entirely clear. In the case of PDE2, however, since cGMP binding to one of the GAF domains clearly activates the enzymatic hydrolysis of cAMP, expression of PDE2 allows stimuli that elevate cGMP levels to reduce cAMP signalling [63]. So far, only a single gene for PDE2, PDE2A, has been identified [64]; however, multiple alternatively spliced isoforms of PDE2A have been reported, some of which are expressed in the same cell [65–67]. Until recently, the only known agent shown to selectively inhibit PDE2 relative to other PDE isoforms was the adenosine deaminase inhibitor, EHNA [erythro-9-(2-hydroxy-3-nonyl)adenine] [68,69]. However, two very potent, selective PDE2 inhibitors developed by Bayer, Bay 60-7550 and Bay 31-9472, both with  $IC_{50}$  values of approx. 4 nM, have since become available and are beginning to be used for probing PDE2 function [70,71].

PDE2 is one of the principal PDEs that is expressed in platelets, where cGMP levels regulate its activity [72,73]. PDE2 has also been reported to represent, along with PDE4, one of the two major forms of PDE in murine thymocytes, where stimulation with PHA caused a transient reduction in PDE2 activity [74]. In contrast with murine thymocytes, PDE2 activity was not detected in resting human CD19<sup>+</sup> peripheral blood B-cells [54] or in purified human CD4<sup>+</sup> and CD8<sup>+</sup> T-lymphocytes [75]. PDE2A is a major PDE induced in monocytes cultured with M-CSF (macrophage colony-stimulating factor) to induce differentiation into macrophages [76].

## PDE3

PDE3 is capable of hydrolysing both cAMP and cGMP; however, since the  $K_m$  for cGMP has generally been reported to be lower than that for cAMP, and the  $V_{max}$  is ten times greater for cAMP than for cGMP, cGMP readily inhibits the hydrolysis of cAMP by PDE3 by acting as a potent competitive inhibitor at the catalytic site [77–79]. Thus expression of PDE3 allows stimuli that elevate cGMP levels to augment cAMP-mediated signalling [78]. There are two PDE3 genes, PDE3A and PDE3B. Cilostazol is a PDE3 inhibitor that is a U.S. FDA (Food and Drug Administration)-approved therapy for claudication, owing to its activity on both platelets and endothelium [80]. Experimentally, milrinone, Org 9355, sigazodon, triquensin, motapizone and cilostamide have been used to specifically inhibit PDE3 isoforms, although it has been shown that milrinone, a commonly used PDE3 inhibitor is less selective for inhibition of PDE3 than cilostazol, and may have some PDE4 inhibitory activity ( $IC_{50}$  16  $\mu$ M) at the concentrations used (typically 1–10  $\mu$ M) to test for PDE3 function [80,81]. Recently, a series of inhibitors showing considerable selectivity for PDE3B over that of PDE3A were developed [82].

In platelets, the predominant PDE3 isoform expressed is PDE3A. Although PDE2-like activity accounts for a greater proportion of basal platelet PDE activity, PDE3 plays a more critical role in regulating platelet aggregation [83]. Nitric oxide-induced cGMP synthesis induces platelet shape changes in a PKA-dependent manner, most likely by inhibiting the activity of PDE3A [84]. Mice rendered PDE3A-deficient by homologous recombination are viable but infertile as a result of an arrest of ovulated oocytes at the germinal vesicle stage. No comment was made of a bleeding diathesis in such PDE3A-knockout animals [85].

PDE3B is the predominant PDE3 isoform expressed in peripheral blood T-cells, where it appears to play a role in the hetero-

logous desensitization processes that follow chronic elevation of cAMP levels [86,87]. Consistent with this, challenge of Jurkat, a cell line derived from T-ALL (acute lymphoblastic leukaemia) cells, with the adenylate cyclase activator forskolin induces both rapid and delayed augmentation of PDE3 activity [88]. Although generally not active alone, PDE3 inhibitors synergize with PDE4 inhibitors to inhibit Th1-mediated immune responses, block mixed leucocyte responses to major histocompatibility antigens and suppress PHA- and anti-CD3-induced T-cell proliferation and IL-2 release [89–93]. Consequently, combined PDE3/4 inhibitors such as zardaverine have been developed [94,95]. Basal PDE3B is also present in human peripheral blood B-cells, where its expression can be up-regulated further in an apparent compensatory fashion following treatment with PDE4 inhibitors [96]. PDE3B is expressed in the K562 erythroid cell line, where it has been suggested to play a role in regulating foetal haemoglobin production [97].

In the myeloid cell line FDPC2, IL-4 induces PKB (protein kinase B)/Akt-dependent phosphorylation and activation of PDE3B [98,99]. Such a pathway is similar to that described for leptin-mediated signalling in the hypothalamus, where PI3K (phosphoinositide 3-kinase) activity results in activation of PDE3B and lowering of cAMP levels [100]. In one study, monocytes derived from atopic subjects showed a relative increase in levels of PDE3B [101], although, in another study, no difference was seen in the activity of PDE3 between normal and atopic subjects [102], and the functional effects of such elevation remain unclear. Within monocyte-derived macrophages, treatment with a combination of PDE3 and PDE4 inhibitors reduced TNF (tumour necrosis factor) secretion to a greater degree than either class of drugs alone [103]. A similar supra-additive effect was observed in relation to dendritic-cell-derived TNF production or in alveolar macrophage-induced arachidonate release [56,104]. In summary, drug therapies based on combined inhibition of PDE3 and PDE4 are likely to lead to more potent suppression of both T-cell and monocyte-mediated inflammatory signalling, an endpoint that may lead to both beneficial and potentially harmful clinical consequences.

## PDE4

PDE4 enzymes are cAMP-specific and play an important role in the biology of haematopoietic cells. These PDEs all hydrolyse cAMP with  $K_m$  values in the range 1–4  $\mu$ M. There are four human PDE4 genes (PDE4A–PDE4D), each of which has multiple splicing isoforms. PDE4 isoforms from all four subfamilies can be divided into 'long', 'short' and 'super-short' groups, depending on the presence or absence of two UCRs (upstream conserved regions) of sequence to the N-terminal side of the catalytic region, termed UCR1 and UCR2. The long forms contain both UCR1 and UCR2, the short forms contain only UCR2, and the super-short forms contain a truncated UCR2. There is also a form of PDE4, PDE4A7, which lacks both UCR1 and UCR2 and has a truncated catalytic region. PDE4A7 is widely expressed, but is catalytically inactive [105]. The function of this inactive form of PDE is unknown. The UCRs are intimately involved in regulating the activities of PDE4 isoforms. The UCR1 contains a serine residue at its extreme N-terminus whose phosphorylation by PKA augments catalytic activity of the PDE4 long forms [106]. PDEs 4B, 4C and 4D also possess a site for ERK phosphorylation near their C-terminal ends, and the presence or absence of UCRs, as well as the state of phosphorylation of UCR1 by PKA, determines the effects of ERK phosphorylation on PDE4 activity. In the absence of PKA phosphorylation, ERK inhibits PDE long forms. However, phosphorylation of PDE long forms in their UCR1

by PKA abolishes this inhibition by ERK. Since inhibition of PDE4 long forms by ERK would be expected to elevate cAMP levels and activate PKA to phosphorylate the PDEs, this no doubt accounts for the transient nature of ERK inhibition of PDE4 long forms. In contrast with PDE4 long forms, phosphorylation of PDE4 short forms by ERK results in their activation [106]. PDE4 splicing isoforms vary in their ability to dimerize, their subcellular distribution and their association with other signalling molecules such as  $\beta$ -arrestin and the immunophilin XAP2 (X-associated protein 2) [106–110]. One splice isoform, PDE4D3, has been shown to form a complex with the cAMP effector PKA as a result of association with an AKAP (A-kinase anchoring protein), with resultant cross-modulation of the activity of the kinase and the PDE [111]. The analysis of mice in which PDE4 genes have been deleted has confirmed that different PDE4 isoforms play markedly different roles in mammalian physiology. PDE4D-knockout mice have both impaired fertility and markedly reduced muscarinic agonist-induced tracheal smooth muscle contraction [112–114]. In contrast, PDE4B-knockout mice have a more than 90% reduction in LPS (lipopolysaccharide)-induced TNF production from circulating leucocytes [115] and more than 50% reduction from peritoneal macrophages [116]. Both isoforms play non-redundant roles in the recruitment of neutrophils to the lung in an endotoxin-inhalation model of lung injury [117].

As a result of the anti-inflammatory properties of PDE4 inhibitors, the pharmaceutical industry has devoted considerable effort to the clinical development of PDE4 inhibitors, with asthma or COPD (chronic obstructive pulmonary disease) as primary indications. Rolipram, one of the first specific inhibitors of PDE4, was studied in the 1980s as a potential therapy for depression or Parkinson's disease, but, despite some evidence of efficacy, development was halted because of the consistent ability of this drug to induce emesis at therapeutically relevant doses [118,119]. Such emetogenic effects of PDE4 inhibitors were ultimately linked to specific PDE4 isoforms, with PDE4D playing a predominant role [120]. More recently, two PDE4 inhibitors, cilomilast (GlaxoSmithKline) and roflumilast (Altana), have undergone clinical trials in asthma and COPD and have demonstrated significant activity in these illnesses [121–123]. Recently, using a novel scaffold-based drug-design method, PDE4 inhibitors were developed by Plexikon which showed several-fold specificity for individual PDE4 subtypes within the PDE4 gene family [124]. Through use of this methodology, a PDE4 inhibitor, PLX513, was obtained which showed an approx. 11-fold selectivity for PDE4B over PDE4D, and this inhibitor was considerably more effective than rolipram in potentiating forskolin inhibition of the proliferation of lymphoma cell lines expressing high levels of PDE4B [125].

PDE4 inhibitors have important effects on the function of both B- and T-lymphocytes. In murine thymocytes, TCR (T-cell receptor) ligation led to an initial reduction followed by a sustained elevation in PDE4 activity [74]. Co-stimulation of human peripheral blood T-cells with anti-CD3 and anti-CD28 results in recruitment of PDE4 isoforms associated with the TCR-CD28 complex to lipid rafts, reducing local cAMP levels and augmenting TCR-mediated signalling [126]. Use of specific antisera identified concomitant recruitment to lipid rafts in such co-stimulated T-cells of a long PDE4A4 isoform, and short PDE4B2 and PDE4D1/D2 isoforms along with  $\beta$ -arrestin and G. Compartmentalization of PDEs to specific microdomains within the cell, along with other components of the cAMP signalling pathway, including adenylate cyclases, G-proteins and PKAs, is essential for controlling localized concentrations of cAMP [127–130]. As an example of the importance of such PDE localization in T-cell signalling, when full-length PDE4B2 is transfected into Jurkat

cells, it associates with lipid rafts and enhances IL-2 production following TCR-stimulation, whereas transfection of a catalytically active, N-terminal truncated form of PDE4B2, unable to associate with lipid rafts, has no effect [131]. It is of note that, while PDE4B2 is the major form of PDE expressed in normal human T-cells, where it associates with the CD3 $\epsilon$  chain of the TCR [132] and plays a critical role in regulating cytokine production during T-cell signalling [131], PDE4B is not expressed at all in the Jurkat [87,88], Molt4 [133] or CEM [134] T-leukaemic cell lines.

PDE4 inhibitors also reduce platelet activating factor, IL-8, IL-15 and SDF-1 (stromal cell-derived factor 1)-induced T-cell chemotaxis [135,136]. In a study of EAE (experimental autoimmune encephalomyelitis), rolipram blocked the production of Th1-type pro-inflammatory cytokines and the development of clinical signs of EAE in mice immunized with myelin basic protein [137]. PDEs 4A, 4B and 4D have been detected in primary human B-lymphocytes [54]. Smith et al. [125] detected the PDE4B2 transcript as the only PDE4B splice isoform expressed in primary naive, centroblast, centrocyte and memory B-cells. Interestingly, PDE4B2 transcript levels were markedly lower in centroblast and centrocytes than in naive B-cells or memory B-cells [125]. Stimulation of human B-cells with LPS and IL-4 augmented cAMP levels and reduced PDE4 activity by 50% [54].

Both monocytes and macrophages express PDE4A7, PDE4A10, PDE4B1, PDE4B2, PDE4C, PDE4D1 and PDE4D2 isoforms [138,139]. In contrast with monocytes, the predominant PDE4 isoform in immature and mature human dendritic cells is PDE4A [140]. Stimulation of T-cells with dendritic cells cultured in PDE4 inhibitors reduced their ability to induce a Th1 response, as judged by a reduction in interferon  $\gamma$ -producing T-cells [140]. In addition to their effects on T-cell and macrophage-mediated recruitment of neutrophils, PDE4 inhibitors have important effects on neutrophil function. The principal species expressed in human neutrophils is the 'short-form' PDE4B2 [141]. PDE4 inhibitors have been reported to inhibit neutrophil degranulation, superoxide generation, zymosan particle phagocytosis and zymosan-induced IL-8 secretion, particularly when combined with adrenergic stimuli such as the  $\beta$ -agonist salbutamol [142–144]. Cilomilast also reduces histamine release from human basophils [145]. In summary, PDE4 inhibitors suppress the human and inflammatory cytokine production of a wide variety of myeloid and lymphoid cells.

## PDE5

PDE5, a cGMP-specific PDE family of considerable importance in regulating smooth muscle and endothelial cell function, is also present in platelets. Although having no effect on platelet function when used alone, PDE5 inhibitors augment nitroprusside's anti-platelet aggregation activity *in vitro* [146]. Although pre-treatment with the PDE5 inhibitor sildenafil has been reported to have significant anti-inflammatory effects in an animal model of airway hyper-reactivity [147], PDE5 activity has not been detected in human circulating T-cells, B-cells or monocytes [54].

## PDE6

In adult human tissues, PDE6, a cGMP-specific PDE that is critical for rhodopsin signal transduction, is highly concentrated on internal membranes of retinal photoreceptors [148]. A single report has suggested that, in mouse F9 embryonal cells, PDE6 may also play a role as an effector for the Wnt (derived from segment polarity gene *wingless* in *Drosophila* and the proto-oncogene *int-1*/Ca<sup>2+</sup>/cGMP signalling pathway [149]. There have been no

publications documenting expression of PDE6 in the haematopoietic lineage.

## PDE7

PDE7A and PDE7B are high-affinity cAMP-specific PDEs with  $K_m$  values for cAMP hydrolysis of approx. 0.2  $\mu$ M (PDE7A) and 0.03–0.1  $\mu$ M (PDE7B) [150–152]. PDE7 was first identified as a high-affinity cAMP PDE in human leukaemic T-cell lines that was insensitive to the PDE4 inhibitor, rolipram [153]. PDE7A1 expression has been detected in human T- and B-lymphocytes, monocytes, neutrophils and alveolar macrophages [91,154,155]. PDE4 and PDE7 both associate with a specific AKAP, myeloid translocation gene, in the Jurkat T-ALL cell line [156], again indicating the widespread nature of PDE compartmentalization. Co-stimulation of T-cells by cross-linking of CD3 and CD28 up-regulates the PDE7A1 and PDE7A3 isoforms [157,158]. Li et al. [157] reported that such PDE7A up-regulation was required for T-cell proliferation, as reduction of PDE7 expression with a PDE7A-specific antisense oligodeoxynucleotide inhibited T-cell proliferation in a manner that could be reversed with a PKA antagonist. However, anti-CD3/CD28-stimulated Th1 and Th2 cytokine production were reported recently to be normal in PDE7A-knockout mice, calling into question PDE7A's role in T-cell activation [159]. Surprisingly, antibody responses to keyhole-limpet haemocyanin are augmented in such mice.

The development of PDE7-specific inhibitors such as BRL 50481 has begun to clarify the potential clinical role of PDE7 inhibition in the treatment of inflammatory illnesses. In studies of CD8<sup>+</sup> T-cells, monocytes and lung macrophages, Smith et al. [160] found that BRL 50481 had little activity when used alone on freshly isolated cells. However, after 'aging' of monocytes in culture led to up-regulation of PDE7A1, BRL 50481 was able to block TNF secretion in a dose-dependent manner [160]. The PDE7 inhibitor also acted in at least an additive manner to reduce TNF secretion when combined with the PDE4 inhibitor rolipram [160]. Similarly, T-2585, a dual PDE4/PDE7 inhibitor, suppressed cytokine production and proliferation of activated human T-cells to a greater extent than that produced by RP 73401 (piclamilast), a PDE4-only selective inhibitor [161].

## PDE8

PDE8A is a widely expressed high-affinity cAMP-specific PDE with highest expression levels in testis, ovary, small intestine and colon [162,163]. In contrast, reports on PDE8B expression are so far limited to the thyroid and brain [164,165]. PDE8 enzymes have quite high affinities for cAMP, with reported  $K_m$  values in the range 40–150 nM [162,163,166]. PDE8 is unique among PDE families in containing a PAS (Per-Arnt-Sim) domain in its N-terminal end. The function of this PAS domain in PDE8 is unknown, but inasmuch as the superfamily of proteins containing PAS domains function to sense changes in the cellular environment, frequently coupling signal transduction pathways to alterations in gene transcription [167,168], PDE8 may serve in some way as an extracellular environment sensor. In that regard, it is noteworthy that a recent report described the PAS-domain-dependent association of human PDE8A1 with  $\kappa$ B (inhibitor of NF- $\kappa$ B (nuclear factor  $\kappa$ B)) proteins, and competition of the enzyme with NF- $\kappa$ B proteins for  $\kappa$ B binding. Binding of  $\kappa$ B to PDE8A stimulated its enzymatic activity 6-fold [169]. No PDE8-specific inhibitors have been reported, although dipyradimole, a non-selective inhibitor most potent on cGMP PDEs, does inhibit PDE8 [162,163,166]. PDE8 is notable in being insensitive to inhibition by methylxanthines such as IBMX (3-isobutyl-1-methylxanthine).

PDE8A1, along with PDE7A3 and PDE7A1, has been reported to be induced in human T-lymphocytes stimulated with anti-CD3 and anti-CD28 antibodies [158], suggesting that PDE8A may play a role in activated lymphocytes, or in the activation process itself. PDE8A1 is constitutively expressed in the human T-cell line, Hut78 [158].

## PDE9

PDE9A is a very-high-affinity cGMP-specific PDE that exhibits a  $K_m$  for cGMP of approx. 70 nM. PDE9A transcripts have been detected at highest levels in spleen, small intestine and brain [170–172]. While PDE9-specific inhibitors are not currently available, PDE9 is inhibited by drugs such as zaprinast and SCH51866, which are also known to be active on PDEs 1 and 5 [170,171]. PDE9, like PDE8, is insensitive to inhibition by methylxanthines. Despite the high level of expression in spleen, no reports examining PDE9 expression or function in haematopoietic cells have yet been published.

## PDE10

PDE10 hydrolyses both cAMP and cGMP and contains GAF domains and a catalytic domain homologous with PDEs 2, 5 and 6 [173,174]. The  $K_m$  of PDE10 for cAMP (50 nM) is much lower than that for cGMP (3  $\mu$ M), and the  $V_{max}$  for cGMP hydrolysis is 5-fold higher than for cAMP, leading to the suggestion that PDE10 may function as a cAMP-inhibited cGMP PDE [27]. The PDE10 transcript is expressed in heart, brain, placenta, testis and kidney, and PDE10 protein in pancreatic islets, but neither has been reported in cells of the haematopoietic lineage [173–175]. The observations that PDE10 is highly expressed in medium spiny neurons of the caudate and putamen regions of the striatum [176], that expression of PDE10 mRNA and protein decrease in transgenic mice expressing exon 1 of the human huntingtin gene [177,178], and that PDE10-knockout mice exhibit decreased locomotion and a synergistic effect on haloperidol-induced catalepsy (Frank Menniti, personal communication), suggest that PDE10 may function in control of motor movement. Inhibitor profiles of PDE10 have been reported [173,174,179]. The enzyme is sensitive to IBMX, and is inhibited by a number of agents that are known to inhibit other PDE families, such as vinpocetine, EHNA, rolipram, dipyradimole, sildenafil and zaprinast, but at concentrations at least severalfold greater. It has been observed, however, that papaverine, a compound used for decades as a general non-selective PDE inhibitor, potently inhibits PDE10 with an  $IC_{50}$  of approx. 30 nM, which is more than 10-fold lower than the concentration at which it inhibits PDEs from any other gene family [180,181]. Given its selectivity for PDE10 at low concentrations, papaverine is now being used to probe physiological functions for PDE10 [182].

## PDE11

PDE11 is a widely expressed dual-substrate PDE that hydrolyses both substrates with  $K_m$  values in the range 0.5–6  $\mu$ M [183–185]. The highest transcript levels of PDE11 are found in skeletal muscle, prostate, kidney, liver, pituitary, salivary glands and testis [184]. Like PDEs 2, 5, 6 and 10, PDE11 contains allosteric cGMP-binding GAF domains. However, splice variants of PDE11 exist which contain only a single GAF domain, whereas all forms of PDEs 2, 5, 6 and 10 identified so far contain two GAF domains [62]. PDE11-knockout mice have been generated, resulting in suppressed spermatogenesis and premature sperm capacitance,

suggesting a role for PDE11 in these processes; however, no gross abnormalities of these mice were seen, and no defects in haematopoietic cells were reported [186]. While PDE11 is sensitive to zaprinast, dipyrindamole and IBMX, no specific PDE11 inhibitors have yet been identified. However, the clinically used inhibitor, tadalafil (Cialis), has dual PDE5/11 inhibitory properties and inhibits PDE11 with an  $IC_{50}$  of approx. 70 nM. The selectivity of tadalafil for inhibition of forms of PDE5 over that of forms of PDE11 has been reported variously as 5-, 14- and 40-fold [187,188]. No reports examining expression of PDE11 in haematopoietic cells have yet been published.

#### EFFECTS OF PDE INHIBITION IN SPECIFIC HAEMATOLOGICAL MALIGNANCIES

As is the case in most areas of cancer research, much of the work examining the role of PDE inhibitors as therapy for haematological malignancies has utilized *in vitro* studies of cell lines derived from patient samples. Such cell lines are likely to maintain some of the genetic alterations that are characteristic of the specific malignancy from which they were derived. Unfortunately, however, cell lines are also likely to differ significantly from such primary malignant cells as a result of the further genetic changes that occur during the selection process required in order to develop the cell line. As an example, primary malignant cells isolated from patients usually do not proliferate in tissue culture to any significant degree, while cell lines do. Nevertheless, for many haematological malignancies, it has been difficult or impossible to carry out extensive experimentation with primary malignant cells. For those illnesses where primary malignant cells are available in abundance, such as B-CLL (chronic lymphocytic leukaemia), it should be acknowledged further that circulating malignant cells may differ significantly from those that are in contact with non-malignant stromal cells in the bone marrow, lymph nodes and spleen, and that culture conditions *in vitro* differ dramatically from the complex signalling environment surrounding such malignant cells *in vivo*. These issues are likely to be of particular importance when studying PDE inhibitors, as the functional effects of these agents will in part reflect basal levels of adenylate or guanylate cyclase activity. With these caveats in mind, we will review what is currently known about the effects of PDE inhibitors on models of specific human haematological malignancies.

#### ALL

ALL is the most common form of leukaemia in children and young adults. Glucocorticoid therapy plays an important role in the successful treatment of ALL patients and *in vitro* glucocorticoid resistance of an ALL patient's lymphoblasts at presentation correlates with an increased risk of relapse following chemotherapy [189–197].

Jiang et al. [49] examined PDE activity in a human lymphoblastoid cell line, RPMI-8392, derived from a patient with ALL. PDE1B1 activity and transcript were detectable in the line, but not in resting HPBLs. Inhibition of PDE1 activity with the inhibitor vinpocetine (100  $\mu$ M) induced apoptosis in RPMI-8392 cells, as well a variety of other cell lines in which the PDE1B transcript was detectable [49]. RPMI-8392 also underwent apoptosis after treatment with the PDE4 inhibitor either rolipram or RO 20-1724. To verify the specificity of the PDE1-inhibitor effect, the authors treated the cell line with an antisense oligodeoxynucleotide to PDE1B or a scrambled control oligodeoxynucleotide [49]. While the antisense oligodeoxynucleotide induced apoptosis and markedly reduced PDE1B transcript and enzymatic

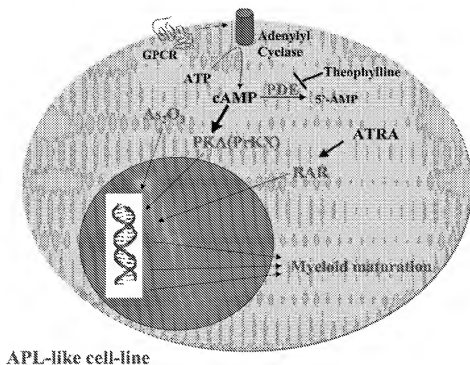
activity, the control oligodeoxynucleotide had none of these activities. Studies on primary ALL lymphoblasts were not performed. The clinical application of these observations remains unexplored.

While ALL cell lines are somewhat sensitive to the induction of apoptosis by agents that augment cAMP signalling, such compounds exert a more striking supra-additive apoptotic effect when combined with glucocorticoids. Myers et al. [198] have reported that treatment with the non-specific methylxanthine PDE inhibitor aminophylline (1,3-dimethylxanthine ethylenediamine) significantly prolonged the event-free survival of SCID (severe combined immunodeficient) mice injected with an ALL-derived pre-B-leukaemic cell line. In studies of the ALL cell line CEM by Ogawa et al. [199], addition of either aminophylline or the PDE4-specific inhibitor rolipram modestly augmented glucocorticoid-mediated apoptosis. Addition of the adenylate cyclase activator forskolin had a considerably more potent effect, particularly when combined with rolipram. Combined rolipram and forskolin treatment also led to up-regulation of p21 and p53 in CEM cells. Tiwari et al. [134], in contrast, found that treatment with rolipram caused no statistically significant augmentation of hydrocortisone or dexamethasone-induced apoptosis in CEM cells, while forskolin markedly augmented such glucocorticoid-induced apoptosis. In keeping with such an observation, forskolin, but not rolipram, augmented CEM cAMP levels. In summary, while it is clear that cAMP-mediated signalling can augment glucocorticoid-mediated apoptosis in the CEM ALL-like cell line, the role of PDE4 in ALL cell lines remains controversial, as does the relationship of CEM cell biology to that of primary ALL lymphoblasts. Future studies will need to be carried out using primary ALL lymphoblasts to determine whether PDE4 inhibitors may be clinically useful as a means by which to increase the efficacy of glucocorticoid therapy in this disease.

#### AML (acute myeloid leukaemia) and the role of cAMP in myeloid development

Traditionally, AML has been treated with cell-cycle-active drugs, such as cytosine arabinoside, and DNA-damaging agents, such as the anthracycline daunorubicin. However, a fundamental shift in the therapeutic approach to this illness occurred with the demonstration that those patients with APL (acute promyelocytic leukaemia), a subset of AML characterized by a 15:17 translocation involving the genes encoding the RAR (retinoic acid receptor) and a protein designated PML (promyelocytic leukaemia), can achieve a remission following treatment with an oral vitamin A derivative alone, ATRA (all-*trans*-retinoic acid) [200]. Instead of inducing apoptosis, by altering the transcriptional regulatory proteins associated with the mutant chimaeric RAR, ATRA releases a developmental arrest in the leukaemic blast cells, allowing the malignant promyelocytes to differentiate normally into mature neutrophils that have a lifespan measured in days. A second successful novel therapy for APL, arsenic trioxide, induces post-translational modifications of PML and apoptosis of APL blast cells, and is now approved for use in APL patients with relapses after ATRA therapy [201]. Recent work [206,208] suggests that agents that augment cAMP-mediated signalling, such as PDE inhibitors, may also relieve developmental arrest in APL and possibly other AML subtypes.

Early studies demonstrated that cAMP analogues, while inactive alone, increased retinoic acid-induced differentiation of APL cell lines [202]. More recently, studies have focused on whether cAMP signalling can augment the ability of the approved therapies ATRA and arsenic trioxide to induce differentiation in APL blast cells. A cDNA microarray analysis



**Figure 2** PDEs as targets for inducing maturation of myeloid cells

It is proposed that PDE inhibitors through their elevation of cAMP can drive the maturation of myeloid cells through the PKA-mediated regulation of transcription. In cell lines and in animal models, PDE inhibitors can synergize with either RAR agonists or arsenic trioxide to drive differentiation of AML blast cells. Of note, PKX, a variant catalytic subunit of PKA that binds to RI (regulatory subunit of PKA) but not to RII (regulatory subunit of PKAII), is expressed in myeloid cells and has been implicated in myeloid differentiation [304,306].

demonstrated that the PKA regulatory subunit  $\alpha$  (PKA-R $\alpha$ ) gene was up-regulated following ATRA-induced differentiation of the APL cell line NB4 [203]. Treatment of either fresh APL blast cells or the NB4 cell line with ATRA rapidly increased cAMP levels and activated PKA. In another report, cAMP analogues were found to increase arsenic-trioxide-induced differentiation of both fresh APL cells and the cell lines NB4 and NB4-R1 (a derivative of NB4 resistant to retinoic acid-induced differentiation) [204]. In a gene expression-based high-throughput screening study, Golub and colleagues examined whether any of the 1739 currently FDA-approved or otherwise biologically well-characterized drugs would induce differentiation of acute myeloid blast cells [205]. Provocatively, five of the eight compounds identified as having differentiative activity [dimaprit dihydrochloride, pergolide methane sulphate, *R*(-)-apomorphine hydrochloride, EHNA hydrochloride and 16-oxoestradiol] had been previously reported to increase intracellular cAMP levels [205]. As at least one of these compounds, 16-oxoestradiol, induced maturation of AML blast cells from a patient with M1 AML, a subtype that is not ATRA-responsive, this study suggested that activation of cAMP signalling pathways may help to drive differentiation in AML subtypes for which differentiative therapies have not yet been identified [205].

Given the experiments cited above, it is not surprising that several groups have now focused on animal models to test the feasibility of improving differentiative therapy for AML with PDE inhibitors. Using PML/RAR $\alpha$  transgenic mice as a model for treatment of APL, Guillemain et al. [206] reported that addition of a constant infusion of 8-Cl-cAMP to either retinoic acid or arsenic trioxide markedly improved clinical outcomes in such mice relative to use of the differentiative agents alone. As noted by the authors, however, the interpretation of such studies is

complicated by the fact that 8-Cl-cAMP is metabolized *in vivo* to 8-chloro-adenosine, a highly active chemotherapeutic agent that in several reports has been argued to account for 8-Cl-cAMP's antineoplastic effects [207]. Guillemain et al. [206] reported further that addition of the non-specific PDE inhibitor theophylline (1,3-dimethylxanthine) to arsenic trioxide synergized in inducing blast cell differentiation in the murine APL model and restored normal haematopoiesis in an APL patient resistant to combined ATRA/arsenic trioxide therapy [206]. Parrella et al. [208] chose instead to investigate the potential utility of specifically inhibiting PDE4 in an *in vivo* model of APL. *In vitro*, the PDE4 inhibitor piclamilast induced PKA-mediated phosphorylation of RAR $\alpha$  and PML/RAR $\alpha$  in the NB4 APL cell line as well as ligand-dependent transactivation. *In vivo*, addition of piclamilast enhanced ATRA-induced maturation of NB4 leukaemia cells that had been implanted into the peritoneum of SCID mice. Piclamilast treatment also enhanced survival of such mice [208]. This study supports the concept of designing clinical trials to determine whether addition of PDE4 inhibitors may reverse resistance to ATRA and arsenic trioxide differentiative therapy in APL. Depiction of a model for targeting PDE as a means of inducing myeloid differentiation is presented in Figure 2.

In addition to driving differentiation in experimental models of myeloid leukaemia, and in contrast with the studies discussed below in which cAMP-mediated stimuli induce apoptosis in susceptible lymphoid cell populations, cAMP-mediated signalling confers an anti-apoptotic effect in many studies of myeloid lineage cells [209–212]. Both dibutyryl-cAMP and forskolin suppress spontaneous human neutrophil apoptosis; in some reports, by a PKA-independent mechanism [212,213]. In the promonocytic U-937 cell line, prior treatment with the non-specific PDE inhibitor theophylline in combination with forskolin



attenuates the induction of apoptosis by etoposide, camptothecin, heat shock, cadmium chloride or X-irradiation [209]. Although the precise mechanism by which cAMP-mediated signalling conferred an anti-apoptotic effect remains unclear, the authors did note that such signalling abrogated the expression of *c-myc*, and blocked etoposide-induced retinoblastoma dephosphorylation and PARP [poly(ADP-ribose) polymerase] cleavage. Similarly, in the promyelocytic HL60 cell line, forskolin, 8-Br-cAMP, the non-specific PDE inhibitor IBMX or the PDE3-specific inhibitor triquetrin inhibited apoptosis induced by paclitaxel or thapsigargin [210]. Curiously, in this model system, the PDE4-specific inhibitors rolipram and RO 20-1724 induced apoptosis within 5 h, although this appeared to occur by a cAMP-independent mechanism. It was reported recently that these same PDE4 inhibitors, rolipram and RO 20-1724, when tested at high concentrations (100–500  $\mu\text{M}$ ), inhibited cyclo-oxygenase-2 expression in T-lymphocytes in a cAMP-independent manner by inhibiting the binding of NFAT (nuclear factor of activated T-cells) to DNA [214]. Inasmuch as Zhu et al. [210] used rolipram and RO 20-1724 at similarly high concentrations of 50–100  $\mu\text{M}$  in their study, and inasmuch as other inhibitors of NFAT signalling, such as cyclosporin A [215] and FK506 [216], induce apoptosis of haematopoietic cells, it is quite possible that the anomalous effect of the PDE4 inhibitors on inducing apoptosis of HL60 cells seen by Zhu et al. [210] may have resulted from an inhibition of NFAT by these inhibitors, rather than an effect on PDE.

The opposing effects of cAMP-mediated signalling on the survival of specific lymphoid and myeloid cell subsets remains thus far largely unexplained. However, it should be noted that, while cAMP promotes apoptosis within lymphoid subsets, as well as some other cell types, including lung and mammary carcinoma cells [34], ovarian granulosa cells [217], fibroblasts [218] and primary cultured cardiomyocytes [219], a considerably wider range of cell lineages, including myeloid cells, pancreatic  $\beta$ -cells, hepatocytes, gastric and intestinal epithelial cells, and spinal motor, superior cervical ganglion sympathetic, dorsal root sensory, dopaminergic, cerebellar granule and septal cholinergic neurons, have been described in which cAMP signalling is anti-apoptotic [220–224]. Whether cAMP-mediated signalling will be pro- or anti-apoptotic, however, appears to depend on a number of different factors, including the nature of the stimulus, the nature of the cAMP effectors that predominate in the cell, the particular locale in which the cAMP signal occurs, and the strength of the signal. In mink lung epithelial cells for example, forskolin or 8-Br-cAMP markedly enhanced TGF $\beta$ 1 (transforming growth factor  $\beta$ 1)-induced apoptosis, but inhibited serum deprivation-induced apoptosis completely [225]. Additionally, whereas  $\beta$ -adrenergic agonists, 8-Br-cAMP and forskolin, inhibited spontaneous as well as Fas-antibody-induced apoptosis of eosinophils isolated from allergen-induced mouse lungs [226], treatment of eosinophils cultured with or without GM-CSF (granulocyte/macrophage colony-stimulating factor) with the PDE4 inhibitor, rolipram, induced apoptosis of these cells [227]. In pancreatic  $\beta$ -cells, forskolin or IBMX, which both produce high cAMP concentrations, as well as cAMP analogues themselves, have an anti-apoptotic effect via an EPAC (exchange protein activated by cAMP)-mediated pathway, whereas GLP-1 (glucagon-like peptide-1) and its receptor agonist, Exenatide, which produce a much more modest elevation of cAMP, produce their anti-apoptotic effect in these cells by activation of the PKA pathway [220].

Interestingly, in addition to being pharmacological targets for inducing or inhibiting apoptosis in some cell types, PDEs have also been shown to be caspase substrates. In rat-1 fibroblasts that undergo apoptosis in response to treatment with forskolin and IBMX, PDE4A5 is cleaved by caspase 3 during the apoptotic

process [218]. Cleavage of PDE4A5 occurs in its unique N-terminal end, and this cleavage results in loss of the ability of PDE4A5 to complex with SH3 (Src homology 3)-domain-containing proteins, a dramatic change in the subcellular distribution of the enzyme, an increase in the catalytic activity of the cytosolic fraction of the enzyme, and a reduction in the catalytic activity of the particulate fraction of the enzyme. Further underscoring the different responses that can result from modulating cAMP in different subcellular compartments or microdomains within the cell, Huston et al. [218] observed that whereas overexpression of PDE4A5 in rat-1 fibroblasts protected them against staurosporine-induced apoptosis, overexpression of PDE4A8, which exhibits a very different subcellular distribution, potentiated staurosporine-induced apoptosis. In addition to PDE4A5, PDE5, PDE6 and, to some extent, PDE10, have been shown to be cleaved by caspase 3 during apoptosis as well [228,229]. In the case of PDE5, the cleavage occurs in the catalytic region and renders the enzyme completely inactive.

### B-CLL: PDE4 as a therapeutic target

B-CLL, the most common leukaemia in adults, is a malignancy characterized by the gradual accumulation of clonal CD5<sup>+</sup>, CD19<sup>+</sup> and CD23<sup>+</sup> mature-appearing B-cells in the bone marrow, spleen and lymph nodes, with resultant anaemia, thrombocytopenia, leucopenia, hypogammaglobulinaemia, infections and autoimmune disease. In early studies, culture with cAMP analogues induced B-CLL cell death [230,231]. However, a clinically feasible means of taking advantage of this observation was first proposed by Mentz et al. [232–234] in studies examining the effects of the non-specific PDE inhibitor theophylline on B-CLL cells *in vitro*. At doses of 50–100  $\mu\text{g}/\text{ml}$ , theophylline, a commonly used therapy for asthma, augmented apoptosis in B-CLL cells [232]. At 4-fold lower doses, theophylline synergized with chlorambucil, an alkylator commonly used in the treatment of B-CLL [233]. Wiernik et al. [235] carried out a phase 2 trial of theophylline monotherapy in patients with early-stage B-CLL. Among 25 patients treated with 200 mg of theophylline given twice a day, there was one complete response and 18 other patients with stable disease. In simultaneous *in vitro* studies, the sensitivity of a patient's leukaemic cells to theophylline correlated with progression-free survival. Although this trial is certainly provocative, interpretation of a non-randomized study in early-stage B-CLL is hampered by the fact that, historically, only a subset of such B-CLL patients would be expected to progress clinically, even in the absence of therapeutic intervention. Theophylline has a narrow therapeutic window as high serum levels can induce tremulousness, nausea, vomiting and seizures. At therapeutic serum levels (5–20  $\mu\text{g}/\text{ml}$ , corresponding to 25–100  $\mu\text{M}$ ), theophylline has only modest inhibitory effects on PDE isoforms *in vitro*. Mentz et al. [234] found that theophylline-induced apoptosis was only partially reversed by the cAMP enantiomeric antagonist Rp-8-Br-cAMPS, (8-bromoadenosine-3',5'-cyclic monophosphorothioate, Rp isomer). They also suggested that theophylline did not synergize with cAMP analogues in inducing apoptosis in B-CLL cells, although the concentration of theophylline used in these studies (100  $\mu\text{g}/\text{ml}$ ) was quite effective in inducing apoptosis by itself and therefore may have reduced the likelihood of observing synergistic interactions with forskolin.

As an alternative strategy, work in our laboratory has examined whether PDE family-specific inhibitors induce cAMP-mediated apoptosis of CLL cells. By Western blot analysis, B-CLL cells express a constitutive  $M_r$  130000 form of PDE3 that co-migrates with recombinant PDE3B, a constitutive  $M_r$  130000 form of PDE4A that co-migrates with recombinant PDE4A5, an

*M*, 64000 rolipram-inducible form of PDE4B that co-migrates with recombinant PDE4B2, an *M*, 70 000 rolipram-inducible form of PDE4D that migrates slightly faster than recombinant PDE4D1, and a constitutive *M*, 55000 form of PDE7 that co-migrates with recombinant PDE7A1 [96,154]. Although CLL samples have detectable PDE1B transcript, only a small subset of leukaemic samples express a constitutive *M*, 74000 form of PDE1 by Western blot analysis that co-migrates with recombinant PDE1B, and enzymatic assays have not identified calmodulin-dependent or vinpocetine-sensitive PDE activity in B-CLL samples to date [236].

To assess the potential ability of family-specific PDE inhibitors to induce apoptosis in B-CLL, leukaemic samples were exposed for up to 3 days to inhibitors, followed by a Hoechst 33342 FACS-based apoptosis assay [236]. The PDE1 inhibitor, vinpocetine, induced apoptosis at 10  $\mu$ M and 30  $\mu$ M, but not at 2  $\mu$ M. Given the absence of detectable PDE1 enzymatic activity in B-CLL cells, the possibility of 'off-target' effects for vinpocetine is of concern. The PDE3-specific inhibitor cilostamide did not induce apoptosis. In contrast, in ten of 14 CLL samples tested, treatment with 10  $\mu$ M rolipram, a PDE4-specific inhibitor, induced apoptosis in at least a third of the leukaemic CLL cells with a range of 38–80% of absolute apoptotic cells. Treatment with forskolin (40  $\mu$ M), an adenylate cyclase activator, had significantly less apoptotic activity than treatment with rolipram, suggesting that adenylate cyclase activity is already of a sufficient magnitude in B-CLL cells *in vitro* that basal PDE4 activity is required to regulate cAMP-mediated signalling, which unchecked leads to apoptosis. The induction of apoptosis by PDE4 inhibitors was significantly slower than that observed for many other apoptotic stimuli, with the majority of apoptosis occurring between 24 and 48 h after the addition of the drug. Treatment with rolipram was associated with elevation of cAMP levels as well as dramatic up-regulation of PDE4B2 transcript and protein levels as a compensatory feedback mechanism [96,236]. Consistent with known defects in CLL B-cell receptor signalling, cross-linking of cell-surface immunoglobulin protected normal circulating B-cells from PDE4-induced apoptosis, but had no such protective effect in B-CLL cells.

A growing literature suggests that combined inhibition of multiple PDE families may be more efficacious than targeted therapy of a single PDE family. In keeping with these observations, we found that inhibition of PDE4 in B-CLL cells *in vitro* led to augmented levels of PDE3B by Western blot analysis, presumably as part of a compensatory feedback loop in response to increased cAMP signalling induced by the PDE4 inhibitor [96]. Although, as noted above, the PDE3 inhibitor cilostamide had no apoptotic effects when used alone, when combined with rolipram, addition of cilostamide (1  $\mu$ M) augmented apoptosis in leukaemic cells from five of seven patients 'resistant' (defined as less than 50% apoptosis after treatment with 10  $\mu$ M rolipram) to the induction of apoptosis by rolipram alone. Thus combination therapy with PDE3 inhibitors and PDE4 inhibitors or use of dual-selective drugs may be of use in a subset of relatively PDE4 inhibitor resistant B-CLL patients.

Sarfati et al. [237] reported that CLL cells were sensitive to the induction of apoptosis by the PDE5 and PDE6 inhibitors sildenafil, vardenafil and methoxyquinazoline. As the authors were unable to detect PDE5, but did detect PDE6, expression in B-CLL cells by microarray analysis, they suggest that aberrant expression of PDE6 may account for the sensitivity of B-CLL cells to these PDE inhibitors [237]. However, the apoptosis  $EC_{50}$  values reported by the authors match the  $IC_{50}$  values of these drugs for PDE4 to a much closer degree than for PDE5 or PDE6 [237]. For example, vardenafil ( $EC_{50}$  1.5  $\mu$ M) has been reported to have

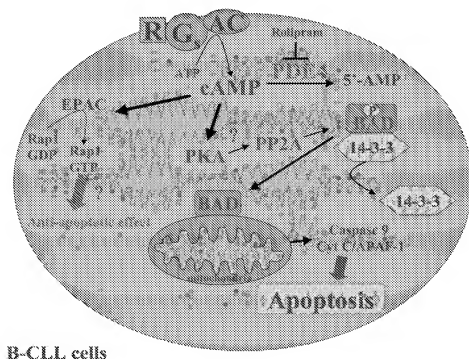
an  $IC_{50}$  of 0.81 nM for PDE5 and 1.91  $\mu$ M for PDE4B [238]. Similarly, sildenafil ( $EC_{50}$  4.1  $\mu$ M) has an  $IC_{50}$  of 7.68  $\mu$ M for PDE4, but 3.5 or 33 nM for PDE5 and PDE6 respectively [239]. Interestingly, the PDE5 inhibitor zaprinast ( $IC_{50}$  of approx. 0.2–0.3  $\mu$ M for both PDE5 and PDE6), which the authors reported was completely ineffective in inducing apoptosis in CLL cells, is also completely inactive against recombinant PDE4A [240–243]. Thus it would appear that the true therapeutic target of these PDE5 inhibitors at these concentrations in B-CLL is PDE4.

B-CLL cells also express PDE7A by Western blot analysis [96]. Although regulation of PDE7 by cAMP has been documented in a human B-cell line, the absence until recently of PDE7-specific inhibitors that lack significant off-target effects has hampered evaluation of PDE7 as a therapeutic target in this disease [154].

#### **DLBCL (diffuse large B-cell lymphoma): PDE4B as a prognostic factor**

DLBCL accounts for approx. one-third of non-Hodgkin's lymphomas. Among patients with advanced DLBCL treated with standard multiagent chemotherapy regimens that contain an alkylator, an anthracycline, a vinca alkaloid and a glucocorticoid, roughly 60% will relapse within 3 years. In 2002, Shipp et al. [244] published a study in which they prospectively assessed diagnostic tumour specimens from 77 DLBCL patients with oligonucleotide microarrays in an effort to identify genes whose expression was predictive of relapse. A predictor containing 13 genes was ultimately identified that correctly classified 32 patients with cured disease from 26 patients with fatal or refractory disease. One of the 13 genes whose expression conferred a poor prognosis was PDE4B. Shipp et al. [244] then performed a retrospective analysis of an independent microarray study of newly diagnosed DLBCL patients by Alizadeh et al. [245] and identified a similar correlation between PDE4B expression and relapse, albeit this was not statistically significant in this smaller study ( $P=0.07$ ). In a subsequent confirmatory study, this group once again observed a statistically significant correlation between PDE4B expression and relapse in set of 112 previously untreated DLBCL patients (57 cured patients and 55 patients with fatal/refractory disease) [125].

The demonstration that PDE4B transcript expression in DLBCL tumour specimens correlates with higher risk of relapse following standard chemotherapy is of great interest, but could potentially reflect quite divergent underlying signalling states in DLBCL tumour specimens. PDE4B transcript levels are augmented as a negative-feedback loop following elevation of intracellular cAMP levels, so DLBCL tumour cells that will ultimately prove refractory to traditional chemotherapy may have such augmented cAMP levels. Such an elevation in intracellular cAMP levels could either be due to an intrinsic alteration in the production or catabolism of cAMP or reflect augmented extracellular signals that activate adenylate cyclase. Alternatively, using a 'selection' rather than a 'compensation' model, PDE4B transcript levels may be higher in resistant DLBCL tumour samples because chemotherapy selected a subset of DLBCL cells that expressed higher levels of PDE4B and were protected from chemotherapy-induced apoptosis as a result of lower cAMP and PKA-mediated signalling (see below). In keeping with this latter hypothesis, it is of interest that Shipp et al. [244] identified high expression of NOR1 (NR4A1), a member of the nerve growth factor 1B family, as correlating significantly with cure in DLBCL, both in their database and that of Alizadeh et al. [245]. As expression of NOR1 is linked to PKA-mediated CREB [CRE (cAMP-response element)-binding protein] activation, DLBCL sensitivity to chemotherapy may correlate with concurrent



**Figure 3** PDE4 as a target for inducing apoptosis in B-CLL cells

PDE4-inhibitor-induced apoptosis in B-CLL cells appears to occur by a PKA-mediated pathway, as the percentage of cells that undergo apoptosis following rolipram treatment is reduced by co-treatment with the PKA antagonist Rp-8-Br-cAMPS. In contrast, activation of the cAMP effector EPAC1 by the EPAC-specific agonist 8-CPT-2Me-cAMP is anti-apoptotic in B-CLL cells. As the net effect of PDE4 inhibitor treatment is to induce apoptosis in B-CLL cells, the pro-apoptotic PKA-mediated pathway appears to predominate over the anti-apoptotic effects of PDE4-inhibitor-mediated EPAC activation. One study reported that PKA signalling induces apoptosis in B-CLL cells by activating PP2A, which in turn dephosphorylates BAD, releasing it from 14-3-3 proteins, and allowing BAD to initiate apoptosis through a mitochondrial pathway. Cyt C, cytochrome c.

PKA-mediated CREB activation, a process that could, conversely, be inhibited in tumour cells that express elevated PDE4B levels [246]. Finally, it is formally possible that elevated PDE4B transcripts identified in DLBCL patients with poor prognosis could derive from non-malignant cells in the tumour specimen. Of note, a recent gene expression profiling experiment carried out in follicular lymphoma demonstrated that prognosis for such patients correlated with the molecular features of the non-malignant immune cells, probably T-cells and macrophages, that are present in the lymphoma tumour specimens at diagnosis [247].

## MECHANISMS OF PDE-INHIBITOR-INDUCED APOPTOSIS

### PDE4-inhibitor-induced BAD dephosphorylation in B-CLL

Dose-titration studies in our laboratory with the PDE4 inhibitor rolipram in primary CLL cells have documented that, unlike prior work in the same cell type with theophylline, a good correlation exists between the degree to which a given concentration of this drug augments levels of intracellular cAMP and the percentage of leukaemic cells induced to undergo apoptosis ( $r^2 = 0.998$ ) [35,234]. Rolipram treatment induces mitochondrial depolarization, cytochrome c release and caspase 9 and 3 cleavage in B-CLL cells [248,249]. Consistent with the hypothesis that such a mitochondrial pathway of apoptosis is critical in rolipram's effects on CLL cells, inhibitors of caspase 9, but not caspase 8, block rolipram-induced apoptosis [249]. Studies have therefore focused on the mechanism by which PDE4-inhibitor-induced augmentation of intracellular cAMP levels results in mitochondrial release of cytochrome c. Co-treatment of B-CLL cells with the enantiomeric cAMP analogue, Rp-8-Br-cAMPS, a known

PKA inhibitor, reduces rolipram-mediated apoptosis, suggesting that rolipram induces apoptosis in this cell type through PKA [250].

Rolipram treatment reduces Bcl-2 and Bcl-X<sub>L</sub> levels and augments Bax levels, suggesting that an alteration in the relative levels of pro- and anti-apoptotic Bcl-2 family members may play a role in triggering cytochrome c release [248]. Rolipram induces Ser<sup>112</sup> dephosphorylation of the pro-apoptotic BH3-only Bcl-2 family member BAD [Bcl-2 (B-cell lymphoma 2 anti-apoptotic protein)/Bcl-X<sub>L</sub> antagonist, causing cell death] in CLL cells, with resulting loss of cytosolic sequestration with 14-3-3 protein and translocation of BAD to mitochondria [249]. Rolipram treatment of B-CLL cells induces up-regulation of PP2A (protein phosphatase 2A)-like enzymatic activity and PP2A catalytic subunit by Western blot analysis. Okadaic acid, a PP2A inhibitor, reduced BAD Ser<sup>112</sup> dephosphorylation and rolipram-induced apoptosis. These studies suggest that PKA may, by an as yet undetermined mechanism, augment PP2A expression and activity in B-CLL cells, resulting in BAD dephosphorylation and the induction of a mitochondrial pathway of apoptosis. A model by which PDE4 may serve as a target for inducing apoptosis in B-CLL cells based on these results is presented in Figure 3.

### Role of EPAC in PDE4-inhibitor-induced apoptosis in B-CLL

In 1998, two groups identified a novel family of Rap1 EPACs (EPAC1 and EPAC2) or cAMP-GEFs (cAMP-activated guanine nucleotide-exchange factors) [251,252]. Subsequent studies identified a cAMP analogue, 8-CPT-2Me-cAMP [8-(4-chlorophenylthio)-2'-O-methyladenosine-3',5'-cyclic monophosphate],

that potentially activates the EPAC enzymes, but not PKA [253]. Studies using this compound have implicated EPAC in integrin-mediated adhesion in epithelial cells and in pancreatic  $\beta$ -cell exocytosis [254,255]. In oligonucleotide array studies, the EPAC1 transcript was expressed at high levels in CLL cells [256]. Tiwari et al. [250] reported that, while the EPAC1 (but not EPAC2) transcript was detectable in normal circulating B-cells and CLL cells, it was undetectable in circulating human neutrophils, monocytes or T-cells. Using real-time PCR, EPAC1 transcript levels were 50-fold higher in B-CLL cells than in normal or activated B-cells. Treatment with the PDE4 inhibitor rolipram in combination with forskolin or even as a single agent led to robust Rap1 activation in CLL cells, but not in normal or activated B-cells, T-cells, neutrophils or monocytes. The hypothesis that such PDE4-inhibitor-induced Rap1 activation was due to EPAC was confirmed by the demonstration that 8-CPT-2Me-cAMP also robustly activated Rap1 in CLL cells, but not in any of the other populations described above.

While rolipram treatment led to both PKA activation (as judged by CREB phosphorylation) and Rap1 activation in B-CLL cells, 8-CPT-2Me-cAMP treatment, as expected, led only to Rap1 activation, allowing an analysis of whether PDE4 inhibitors induce apoptosis through a PKA or EPAC-mediated pathway. Surprisingly, activation of EPAC with 8-CPT-2Me-cAMP reduced basal apoptosis in B-CLL cells. Thus, in B-CLL cells, it appears that PDE4 inhibitor treatment activates two pathways, a pro-apoptotic PKA-mediated pathway whose effects predominate over anti-apoptotic effects mediated by EPAC1 (see Figure 3). Although the mechanism by which EPAC1 activation confers such an effect in B-CLL remains undetermined, it is notable that two other groups examining pancreatic  $\beta$ -cells and hepatocytes have also reported 8-CPT-2Me-cAMP to be anti-apoptotic [220,221]. In the hepatocyte study, Webster and colleagues reported that EPAC activation is anti-apoptotic as a result of PI3K and PKB/Akt activation [221].

#### Role of GR (glucocorticoid receptor) signalling in PDE4-inhibitor-induced apoptosis

Those subsets of lymphoid cells that are sensitive to cAMP-mediated apoptosis tend also to be sensitive to glucocorticoid-mediated apoptosis. While the human T-ALL cell line CEM undergoes apoptosis following exposure to cAMP analogues, McConkey and colleagues observed that a GR-defective variant of this cell line, ICR.27, was resistant to cAMP-mediated apoptosis. Stable transfection of ICR.27 with GR restored sensitivity to the cAMP analogues, suggesting that cAMP-induced apoptosis requires at least some aspect of GR function [257]. Consistent with such 'cross-talk', the catalytic subunit of PKA has been reported to associate with the GR [258].

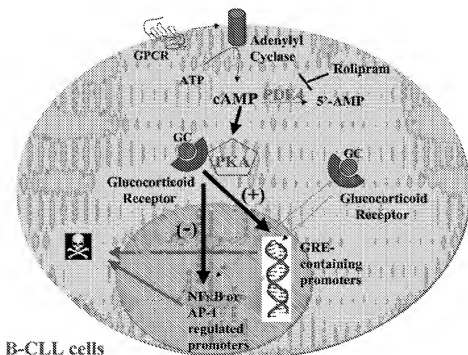
cAMP signalling also augments glucocorticoid-induced apoptosis, a potentially important phenomenon as glucocorticoids continue to play a key role in chemotherapeutic regimens for ALL, DLBCL and multiple myeloma [199,259–261]. In a study of primary leukaemic cells from patients with B-CLL, Tiwari et al. [134] identified PDE4 inhibitors as a clinically feasible means by which to take advantage of such enhancement of glucocorticoid-mediated apoptosis by cAMP signalling. Rolipram or RO 20-1724 synergized with either hydrocortisone or dexamethasone in inducing apoptosis in B-CLL cells but not primary T-cells. As had previously been reported in studies of glioma cells, rolipram treatment of primary B-CLL cells enhanced hydrocortisone-induced transactivation of transiently transfected GRE (glucocorticoid-responsive element) promoter-containing luciferase constructs [262]. Prior treatment with the PKA antagonist Rp-8-

Br-cAMPS markedly reduced glucocorticoid-mediated apoptosis in B-CLL cells, suggesting that the basal level of PKA activity in leukaemic cells may dictate the effectiveness with which glucocorticoid therapy induces apoptosis in such cells. A model depicting the synergistic effects of glucocorticoids and PDE4 inhibitors on induction of B-CLL cell apoptosis is presented in Figure 4.

Ideally, it would be of interest to similarly determine whether modulation of GR function with a GR antagonist alters the ability of PDE4 inhibitors to induce apoptosis in B-CLL. Unfortunately, in findings similar to those reported by Gruol and Altschmid [260] in immature murine T-cells, while the best characterized GR antagonist mifepristone (RU 486) had no activity when used alone on B-CLL cells, it acted as a GR agonist when combined with either rolipram or other drugs that activate PKA signalling. Refojo et al. [263] have argued that cAMP-mediated potentiation of glucocorticoid-mediated apoptosis is independent of CRE transcriptional activation as it was unaffected by co-transfection of CRE 'decoy' oligonucleotides that effectively inhibited transcription of *bona fide* CRE-containing promoters [263]. In aggregate, these studies support clinical trials to investigate whether the addition of PDE4 inhibitors to chemotherapeutic regimens in which glucocorticoids play an important role will enhance the efficacy of such therapies.

If cAMP and PDE4 inhibitor-mediated apoptosis is in fact mediated to an important degree through the activity of the GR, the mechanism by which glucocorticoids themselves induce apoptosis remains a subject of some controversy. Although the GR was initially characterized as a DNA-binding transcription factor that was capable of activating GRE-containing promoters, the medically beneficial anti-inflammatory activity of glucocorticoids appears to be the result of GR-mediated 'transrepression' of signalling by a variety of other transcription factors such as AP-1 (activator protein 1) and NF- $\kappa$ B through a tethering mechanism that is independent of the GR's DNA-binding activity [264]. Thymocytes from 'knockin' mice that express the A4587 GR are unable to transactivate GRE-containing promoters as a result of a point mutation that abrogates dimerization of the GR. Thymocytes from such 'GR<sup>dim</sup>' mice are resistant to glucocorticoid-mediated apoptosis, suggesting that, at least in this normal lymphoid population, glucocorticoid-mediated apoptosis is mediated by the GR's transactivation activity [265]. In contrast, glucocorticoid-mediated apoptosis of cell lines derived from lymphoid malignancies appears to be dependent upon the transrepressive activity of the GR [266]. Whether, with regard to the mechanism by which steroids (and PDE4 inhibitors) induce apoptosis, primary malignant lymphoid cells such as CLL cells resemble to a greater degree normal thymocytes or cell lines derived from malignant cells will require experimental techniques that allow one to address these questions within a primary malignant cell population.

The synergistic effect of glucocorticoid and cAMP signalling pathways on apoptosis may also result, in part, from effects of glucocorticoids on the expression and regulation of PDEs. Early studies on cultured hepatoma cells showed that long-term incubation of cells with dexamethasone led to a 25–40% decrease in PDE activity and markedly enhanced the elevation of cAMP in the cells in response to adrenaline and theophylline [267]. Subsequent studies with cultured rat hepatocytes showed that dexamethasone selectively reduced the transcription of PDE4D [268]. Similarly, a recent study in human osteosarcoma cells showed that long-term treatment with dexamethasone selectively decreases the mRNA of PDE4A4 and PDE4B1 by 50–70% [269]. In human T-lymphocytes, beclomethasone attenuated the long-term induction of PDE activity that occurs following activation by PHA or IL-2 [270]. Long-term incubation of murine T-cell



**Figure 4** PDE4 inhibitors augment glucocorticoid-induced apoptosis of B-CLL cells

In B-CLL cells that are relatively resistant to apoptosis induced by either hydrocortisone or dexamethasone, co-treatment with rolipram can increase the percentage of apoptotic cells in a supra-additive manner. Experiments with GRE-containing luciferase reporter constructs demonstrate that rolipram treatment also augments glucocorticoid-mediated apoptosis and glucocorticoid-induced GRE activation in B-CLL cells, suggesting that levels of PKA activity may serve as a 'rheostat' that determines the apoptotic outcome of glucocorticoid therapy in this B-cell malignancy. Although the precise mechanism by which PKA activity modulates glucocorticoid-induced apoptosis remains unknown, the catalytic subunit of PKA has been reported to associate with the GR and to phosphorylate co-activators or co-receptors that are associated with this transcriptional complex. Notably, the mechanism by which GR signalling induces apoptosis in lymphoid cells remains controversial. GR-mediated apoptosis could involve either transactivation of GRE-containing promoters or GR-mediated *trans*-repression of other transcription factors such as NF- $\kappa$ B or AP-1 (activator protein 1) through a tethering mechanism that does not require a functional GR DNA-binding domain. GC, glucocorticoid; GPCR, G-protein-coupled receptor.

hybridomas with dexamethasone results in a 32–65% decrease in PDE4 activity and a 5-fold increase in cAMP levels [271]. Hence, multiple effects of glucocorticoids on cAMP signalling may account for the observed synergism between these two signalling pathways, including effects of glucocorticoids on PDE4 expression.

#### DLBCL: cAMP-mediated PI3K and Akt activation

To examine the explanation for the correlation between high PDE4B transcript levels in newly diagnosed DLBCL tumour specimens and relapse after chemotherapy, Smith et al. [125] carried out a study with DLBCL cell lines. Transfection of DHL6, a line with low basal PDE4B expression, with a PDE4B2 expression construct reduced intracellular cAMP levels after treatment with forskolin (40  $\mu$ M) and protected these cells against forskolin-induced growth arrest and apoptosis. Surprisingly, PCR analysis and experiments performed with the PKA inhibitors H-89 and a PKI (cAMP-dependent protein kinase inhibitor)-derived peptide suggested that neither PKA nor EPAC are relevant effector proteins of forskolin-mediated apoptosis in this model system.

Smith et al. [125] detected a marked reduction in Akt Ser<sup>473</sup> phosphorylation in rolipram/forskolin-treated DHL6 cells with maintenance of total Akt levels, while such a reduction in Akt phosphorylation was not detected in DHL6 PDE4B stable transfectants following the same treatment. As incubation of DHL6 cells with rolipram and forskolin also markedly reduced levels of  $\text{PtdIns}(3,4,5)\text{P}_3$ , the product of PI3K, the authors hypothesize that

cAMP-mediated signalling by an as yet uncharacterized effector protein leads directly or indirectly to inhibition of PI3K activity, with a resultant reduction in Akt phosphorylation. The authors conclude that co-treatment with PDE4B and PI3K/Akt inhibitors may serve to reduce resistance to apoptosis in DLBCL. These results are depicted in a model presented in Figure 5.

#### Specificity of PDE4-inhibitor-induced apoptosis

cAMP-induced apoptosis is limited to small subsets of normal lymphoid cells, lymphoid cell lines and lymphoid neoplasms. PDE4-inhibitor-induced apoptosis occurs within a yet smaller subset of these cAMP-sensitive lymphoid cell populations. What accounts for the specificity of PDE4-inhibitor-induced apoptosis? One potential mechanism for such specificity might theoretically be that of so-called 'flux-mediated sensitivity' [24], meaning that those cell populations with robust basal adenylate cyclase activity would be markedly more sensitive to cyclic nucleotide PDE inhibitors than cells in which the basal rate of synthesis of cAMP is low. While, from limited data, it does appear that treatment of B-CLL cells with PDE4 inhibitors alone leads to a greater elevation in intracellular cAMP levels than comparable treatment of whole mononuclear cells, a predominantly T-cell population, it does not appear that this accounts for the relative sensitivity of B-CLL cells to PDE4 inhibitors [236]. Thus treatment of either isolated T-cells or whole mononuclear cells with a combination of rolipram and forskolin results in markedly higher levels of intracellular cAMP than those observed in CLL cells treated with PDE4 inhibitors alone, yet the rate of apoptosis

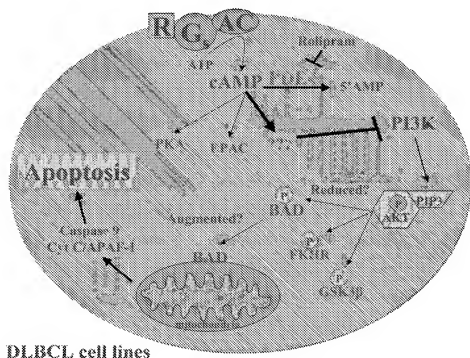


Figure 5 PDE4 inhibitors induce apoptosis in DLBCL cell lines

Elevated levels of PDE4B2 protect DLBCL cell lines from forskolin-induced apoptosis, and PDE4B-selective inhibitors overcome this, allowing forskolin to elevate cAMP levels and induce apoptosis. In this case, cAMP was reported to act neither through EPAC nor through PKA, but instead through an as yet undefined effector to inhibit PI3K, thereby reducing PKB/Akt activity and consequent phosphorylation of BAD. Dephosphorylated BAD can then induce apoptosis through the mitochondrial pathway. Alteration of the phosphorylation state of other PKB/Akt phosphorylation targets such as FKHR (forkhead in rhabdomyosarcoma) [309] and GSK3 $\beta$  (glycogen synthase kinase 3 $\beta$ ) [307] may also contribute. Cyt C, cytochrome c; PI3K, Phosphoinositide 3-kinase.

induced in such rolipram/forskolin-treated T-cells remains very low [236]. Thus levels of total intracellular cAMP clearly do not mirror rates of apoptosis in sensitive and resistant lymphoid populations.

Alternatively, the unique sensitivity of specific lymphoid subsets to PDE4 inhibitors could be accounted for by the expression of particular PDE4 isoforms that regulate cAMP signalling pathways whose unfettered activity triggers apoptosis. This hypothesis also does not hold up under scrutiny, as the PDE4 isoforms expressed in B-CLL cells; PDE4A5, PDE4B2 and PDE4D1/D2, have all been reported in PDE4 inhibitor-resistant cell types, such as T-cells. It should be noted, however, that this summary does not take into account the basal levels of PDE4 isoforms expressed in such cells before challenge with a cAMP signalling stimulus. The work by Smith et al. [125] in DLBCL cell lines has demonstrated that elevating basal levels of PDE4B2 protect cell lines that are initially sensitive to forskolin-induced apoptosis. Whether such forskolin-induced cAMP signalling in cell lines sheds light on the apoptosis induced by treatment with the PDE4 inhibitor alone in susceptible primary lymphoid cells remains to be seen.

Thus, while elevation of intracellular cAMP levels and the presence of particular PDE4 isoforms may both be necessary for PDE4-inhibitor-induced apoptosis, they are not sufficient. The specificity of this form of apoptosis lies downstream, either potentially in the specific subcellular organization of the effectors and regulators of cAMP-mediated signalling in these lymphoid cells or in the specific targets of PKA or other unidentified effector proteins. As noted above, the details of such downstream pro-apoptotic signalling pathways remain controversial and beckon further exploration.

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